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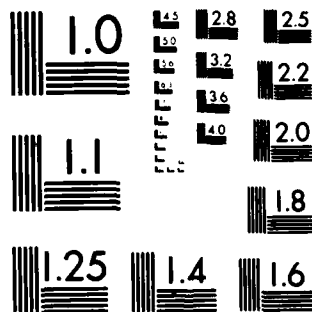   ROCHESTER NY   P S NEELAKANTASWAMY JAN 87 RITRC-009
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Failure of equipment-mounted devices due to indirect (noninvasive) energy transfer from the ESD via transient electromagnetic coupling/interference warrants a unique modeling as detailed in this report.

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IMPULSIVE EMI RADIATED BY ELECTROSTATIC DISCHARGES (ESD)

Failure of equipment-mounted devices due to indirect (noninvasive) energy transfer from the ESD via transient electromagnetic coupling/interference warrants a unique modeling as detailed in this article.

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Conventional studies on ESD-based damages are invariably restricted to chip-level.[1] However, there has been an increased awareness recently to investigate the susceptibility of equipment and subassemblies to ESD failures,[2,3] because such larger systems would present prominent cross-sections of exposure to impulsive electromagnetic interference (EMI) emanating from an external ESD event.[4] That is, equipment, in general, is potentially propensive to accept electromagnetic waves radiated from an external ESD occurring in the vicinity. Therefore, any sensitive device mounted within the equipment is likely to be damaged by absorbing the interfering electromagnetic energy penetrated through apertures (on the equipment-shielding) and/or coupled via conductor surfaces, connectors, etc. Eventually circuit malfunctioning and/or equipment-breakdown would occur depending on the failure being latent-type or catastrophic. Appearance of

"ghost-bits" and "bit dropouts" in computers and "sneaky" equipment failures in production lines, in the inspection departments, at tne stockroom, while-on-transit or in fields, etc., can be largely attributed to such ESD-based electromagnetic influences.[5] To evaluate the cause-effect relations quantitatively in the aforesaid failure-mode, it is essential to develop an EMI model representing the ESD-excited electromagnetic wave, its coupling to devices via equipment/subassembly cross-section(s) and the resulting damage. This article proposes a model to portray exclusively the implicit (EMI-based) ESD-to-device interaction in contrast with the existing models (human-body model,[6] charged-device model[7] and field-induced model[8]) which rather describe the direct (contact-based) interactive damages.

ESD MODELS

The electrostatic discharge (ESD) phenomenon that plagues the modern electronic industry as a new contaminant, is normally simulated by three well-established models[6,7,8] describing the device to ESD interactions: The human-body model[6] shown in Figure 1 depicts the transfer of static from a charged person to ground via the test device. Charged-device model[7] (Figure 2) represents the bleed-off of accumulated charges (which "normally stay put as puddles" upon the device-surface) to ground through the pin(s) and/or conductive parts of the active device. The third model[8] simulates the effect of the charge distribution and discharge when a device is exposed to a static-electric field (Figure 3).

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In general, ESD threats modeled as per Figures 1-3 are conceived and supposedly experienced only in isolated devices; that is, in those devices which are not subassembled or mounted on PCBs of the equipment. This presumption is rather incorrect and as pointed out by Frank[9], it is a "myth" to presume "an ESD sensitive component cannot be damaged once it is installed on a circuit board." Notwithstanding, in the existing practice, the survivability assessment of electronic systems under electrical overstress (EOS) arising from ESD have been invariably restricted to analyze isolated components only and failure prevention measures have been prescribed accordingly--only to the handling and using of isolated devices. Further failure threshold studies and protective circuit designs have been mostly based on anticipated ESD threats exclusive to unmounted/isolated devices.

However, case studies reveal that devices mounted on printed circuit boards (PCB) in equipment would experience high failure rates under ESD environments despite exercising the prescribed precautionary measures. For example, as indicated by Thompson,[2] non-observance of ESD protective measures in handling and using certain costly replacement subassemblies of tactical systems like missiles, resulted in excessive loss and warranted frequent field-repairs.

Not taking care to protect ESD sensitive components from the damage after they have been installed in an equipment can also result in performance degradation of the unit, as pointed out by Frank[9] referring to a

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case of scientific calculator being not able to retain the programmed memory when necessary handling procedures were not followed.

More evidence on ESD-induced damage to integrated circuits on PCBs has been recently furnished by Shaw and Enoch[10] with experimental data pertaining to the sensitivity of a batch of octal-latch integrated circuits mounted on a printed circuit board to ESD transients. Their experiments reveal that high static propensity of PCBs would lead to an ESD transient sufficiently large enough to cause catastrophic damages in mounted devices.

Recently, the author has also studied[3] the susceptibility of PCB-mounted devices to failures caused by ESD and indicated the higher vulnerability of subassembled structures.

EMI MODEL

In ESD problems related to subassembled and/or equipment-mounted devices, the threat would arise not only from direct/contact-based bleed-off of electrical charges, but also due to noninvasive electromagnetic coupling (Figure 4). That is, as mentioned[11] in DOD-HDBK-263, electromagnetic pulses (EMP) caused by ESD in the form of a spark can cause part failures in equipment.

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The following analysis will enable a simulation/modeling to represent such noninvasive ESD-base EMI threats. Consider an ESD event, say, from a finger tip occurring in the vicinity of a circular aperture on an equipment (shielding) as illustrated in Figure 5. For the purpose of analysis, the finger is regarded as a dielectric-wedge (vide the insert in Figure 5) inducing an intense electric field in the discharge gap. The propagating, transient electromagnetic field generated at the gap can be represented by the lightning function as follows:

$$e_1(t) = E_1[\exp(-At) - \exp(-Bt)] \tag{1}$$

with A and B being constants dependent on the rise and decay times of the impulse discharge. The amplitude E_1 at the center of the discharge-gap is proportional[6] to $\tau \, D^{\tau-1}$ where D is the gap-width and τ is a parameter ($0 < \tau < 1$) dependent on the wedge-angle (α) and on the ratio of dielectric constants, $\varepsilon_2 / \varepsilon_1$. The electric field E_1 becomes singular attaining infinitely large magnitude as D approaches zero. This enhanced local field (E_1) due to the wedge-like structure of the finger can be evaluated by the analysis due to Meixner.[12]

As the induced field is intercepted by the circular aperture on an (invariably) grounded and charge-free equipment-shield, the corresponding electromagnetic wave interior to the shielding is related to the exterior field components by means of a coupling coefficient (K) given by[13]

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$$K = \frac{1}{\pi}[\theta_o - \frac{\sin\theta_o}{2} - \frac{\sin 2\theta_o}{2} - \frac{\sin 3\theta_o}{6}] \tag{2}$$

where θ_o is the semiangular width of the circular aperture, assumed to be located on a large, hollow, spherical shield (Figure 5) of radius, ρ.

The penetrated EMI is incident on a lossy dielectric sphere (of microscopic dimension) representing the vulnerable part ("hot-spot") in the microelectronic device, presumed to be located at the center of the spherical shield. The peak absorbed energy (W) at the dielectric sphere (with complex permittivity equal to $\varepsilon' - j\varepsilon''$) can be determined by the spherical wave expansion technique (Mie solution) due to Stratton[14] with appropriate boundary conditions and small argument approximations and by expressing the EMI field in the frequency domain through Fourier transform method. The result is,

$$W \simeq (4\pi a^3/3)\sigma K^2 E_1^2 \left| F(R,\theta,\phi) \right|^2 (B-A)^2/(B+A) \tag{3}$$

where $\sigma = \omega\varepsilon.\varepsilon''$ and,

$$\left| F(R,\theta,\phi) \right|^2 = [9/(\varepsilon'^2 + \varepsilon''^2) + 0.4(k_o a/2)^2], \tag{4}$$

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with k_o being the free-space propagation constant.

If A_J is the junction area in the device, $W/A_J\tau_o$ would refer to the average power density over a pulse duration, τ_o. Presuming that the failure occurs at t_d, the quantity $W/A_J\tau_o$ can be equated to the Wunsch-Bell's limit[15] of catastrophy (due to junction burnout) and the corresponding result yields an expression for the damage-time (t_d) as:

$$t_d = \tau_o^2 a_J^2 (T_m - T_i)^2 (\pi k_d \rho_o C_p)/W^2 \tag{5}$$

where T_m and T_i are the melting point and initial temperature of the device, respectively; further, the quantities k_d, ρ_o and C_p, respectively, refer to thermal conductivity, density, and specific heat of the device material.

The results on damage-time (t_d) as a function of the rise-time (τ_r) of the excited transient field (Equation 1) indicate that the relative damage-time t_{d1}/t_{d2} (corresponding to two rise-times, namely, τ_{r1} and τ_{r2}) is approximately equal to $(\tau_{r1}/\tau_{r2})^2$ assuming that the pulse duration (τ_o) is constant and τ_r is equal to $\ln(B/A)/(B-A)$. In the computation, the value of k_o was taken approximately equal to $2\pi/c\tau_r$ (with c being the free-space

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velocity of the electromagnetic wave); further, the square-law relation between the relative values of t_d and τ_r is found to be valid, irrespective of the material of the device (that is, either silicon or GaAs).

The author has indicated elsewhere[16] that the relative damage-time directly specifies the lethality endurance coefficient (LEF) of the device. Hence, it follows from the present analysis that the LEF is equal to $(\tau_{r1}/\tau_{r2})^2$.

EXPERIMENTAL STUDIES

As radiated interference results from discharges to nearby conducting objects, the currents flowing through the conducting surface would create transient electromagnetic waves which can be picked up by wires acting as antennas interpreted as valid signals; or, the interference can also directly invade the devices causing catastrophic or latent failures. The extent of lethality is governed by the analysis indicated before.

The existence of ESD-based EMI can be verified by an experiment simulating the ESD-sparking environment. Per DOD-HDBK-263, ESD spark testing[11] can be performed by discharging the ESD in the form of a spark across a spark-gap sized for the ESD test voltage or by slowly bringing the high voltage test lead of the test circuit close to the case or electrical terminal of an ESD sensitive item while it is operating until the voltage is discharged in the form of an arc.

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More elaborate test methods have been described by Honda and Ogura[17] who utilize time-domain and frequency-domain methods for quantitative prediction of ESD-based EMI.

Presently a simple arrangement is described to simulate the test studies under discussion. The principle of the test method is depicted in Figure 6, and Figure 7 illustrates the actual experimental set-up used.

A human-body zap simulator (IMCS Model 2600) is used to establish the spark across a metal tip and a grounded metal sheet. The simulator can provide positive or negative 25v to 25 kV peak, single or sequenced (5 or 10) pulses with variable ramp up rate of 5 to 25 kV/sec. The pulse mode operation corresponds to the human-body ESD of Figure 1.

The equipment/subassembly is simulated by portable static sensor (RITRC-1000) developed by the RIT Research Corporation. It is a miniaturized static sensor (originally developed to evaluate the efficacy of ESD protection bags) mounted on a PCB with an associated circuitry to respond with audio (buzzer) and video (LED) annunciations when the sensed static or static-induced electric field exceeds a present level.

The sensor was enclosed in an EMI shield (metallic sandwich box) with a small coupling hole of 1/4" diameter. It was placed at a convenient distance (d) from the induced spark, such that for a given discharge voltage (peak) V_s and ramp rate $(r=\dfrac{di_s}{dt})$ the sensor would annunciate the reception of

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EMI. For a given gap width at the spark, it was observed that the sensor response level was proportional to product of V_s and r.

The test performed confirms the possible noninvasive interaction between an ESD and a nearby equipment via electromagnetic coupling; and quantitatively, such an interference is governed by the arc gap-width, coupling cross-section and the product of V_s and r.

CONCLUSIONS

From the analytical discussion presented before and from the experimental results obtained, the following conclusions can be inferred:

1. Quantification of EMI coupling reveals that the extent of severity involved primarily depends on the ESD source and the coupling through the shield.

2. The intrinsic lethality of the device is mainly a function of the electrothermal parameters of the junction in the vulnerable device.

3. The intensity and rise-time of the transient ESD overwhelmingly dictate the extrinsic-dependency of the device-lethality.

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4. The present analysis also indicates that the influence of ESD via EMI is governed by the gap-width (D), as experimentally observed by Honda and Kawamura.[4]

5. The overall lethality of the device is directly proportional to the effective cross-section of the equipment exposed to the EMI, quantified via the coupling coefficient, K.

6. Intense EMI coupling would be experienced if the ESD event is provoked by short-tips or wedges.

7. The implicit dependency of device-lethality on the transient nature of the ESD (expressed in terms of τ_r) as evinced in the present work, concurs with the results due to Honda and Kawamura[4] who expressed the EMI severity in terms of the voltage and rate of change of current product (V_s x di_s/dt) pertaining to the ESD loop (Figure 5).

8. Lastly, the relative lethality of the device to transient discharges is equal to the square of the relative rise-times of the transients.

There are two possible solutions against radiated interference from an ESD. The first method is simply to make the overall equipment shield as complete as possible. That is, making the shield a nearly seamless six-sided box, would reduce or eliminate the internal fields induced by the invading interference.

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However, for cosmetic reasons, if a complete metal-housing is not possible, the second approach is to adopt second internal shields exclusive to ESD-sensitive PCBs and connect the second shield to the first (external shield) at the electrical power inlet. By this arrangement, the outer shield acts as radiating plane producing fields in its interior, the second shield, at the same time does not have induced current flowing through it. Similar effect can also be activated by a ground-plane under the PCB or multilayer board with a buried ground plane.

ACKNOWLEDGEMENT

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CAPTIONS FOR THE DIAGRAMS

Figure 1: ESD: Human-Body Model

Figure 2: ESD: Charged-Device Model

Figure 3: ESD: Field-Induced Model

Figure 4: EMI Due to Static Effects

Figure 5: ESD-Based EMI: Modeling

Figure 6: Principle of Simulating ESD-Based EMI

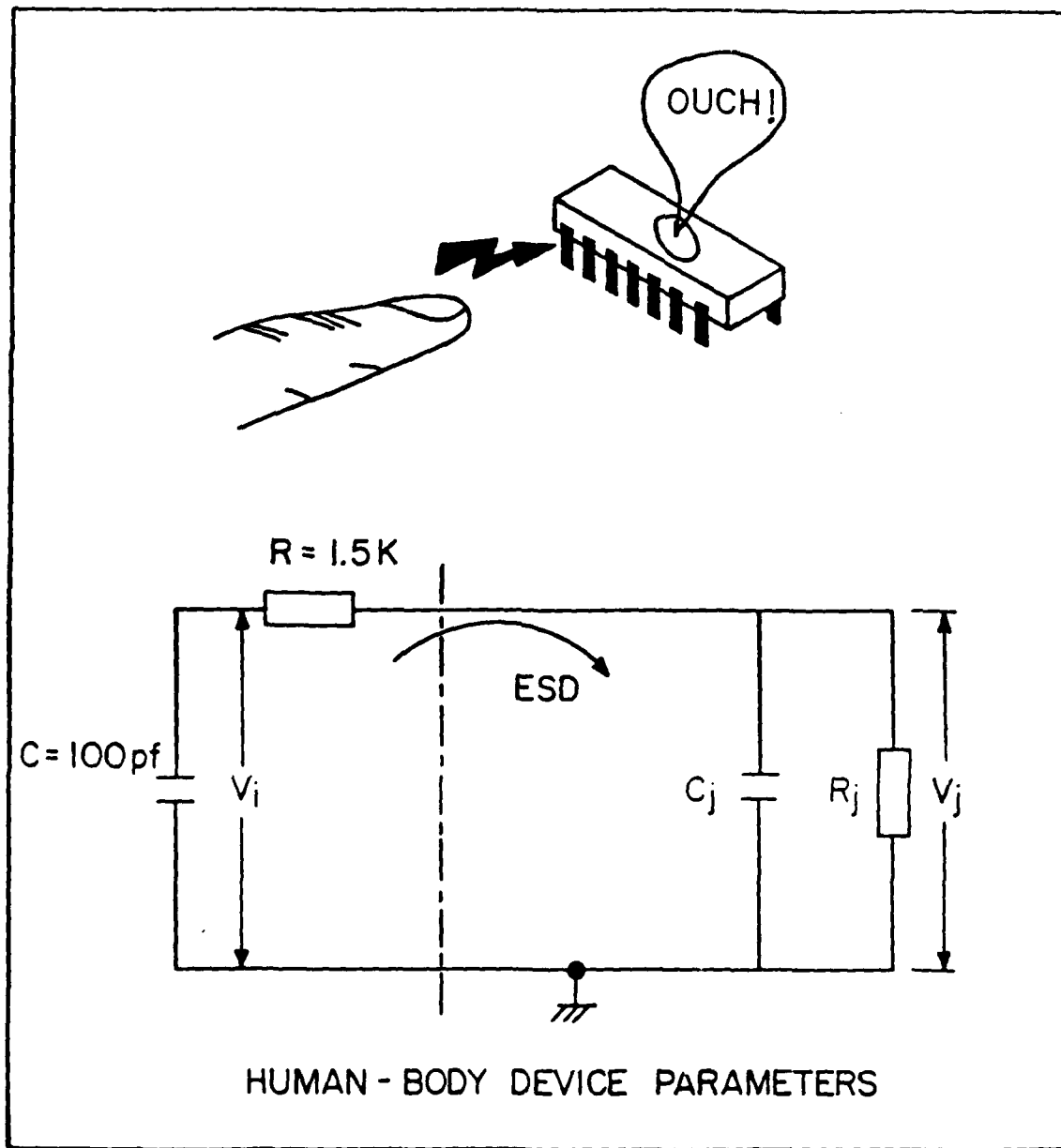Figure 7: ESD-Induced EMI Coupling To A Circuit: Experimental Set-Up
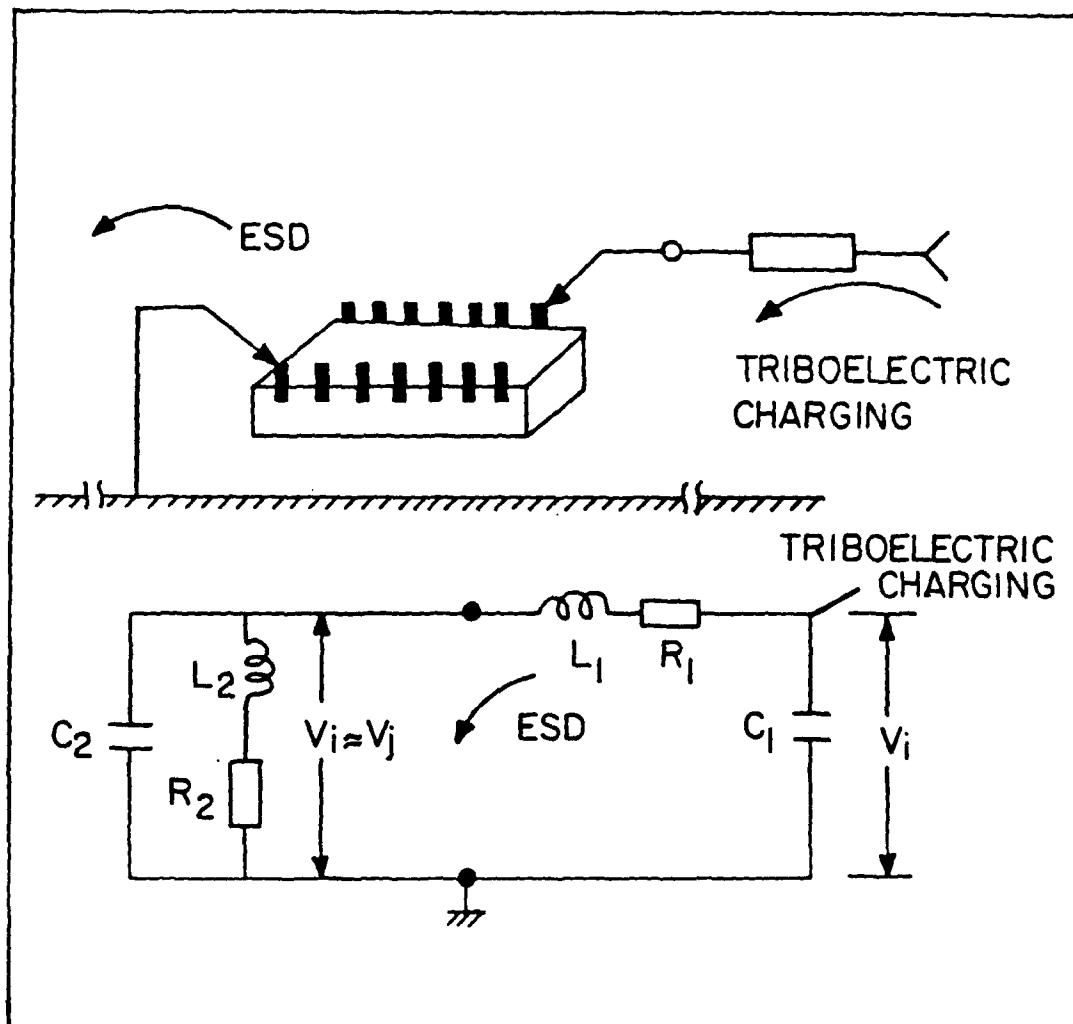
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FIG. 1   ESD: HUMAN-BODY MODEL

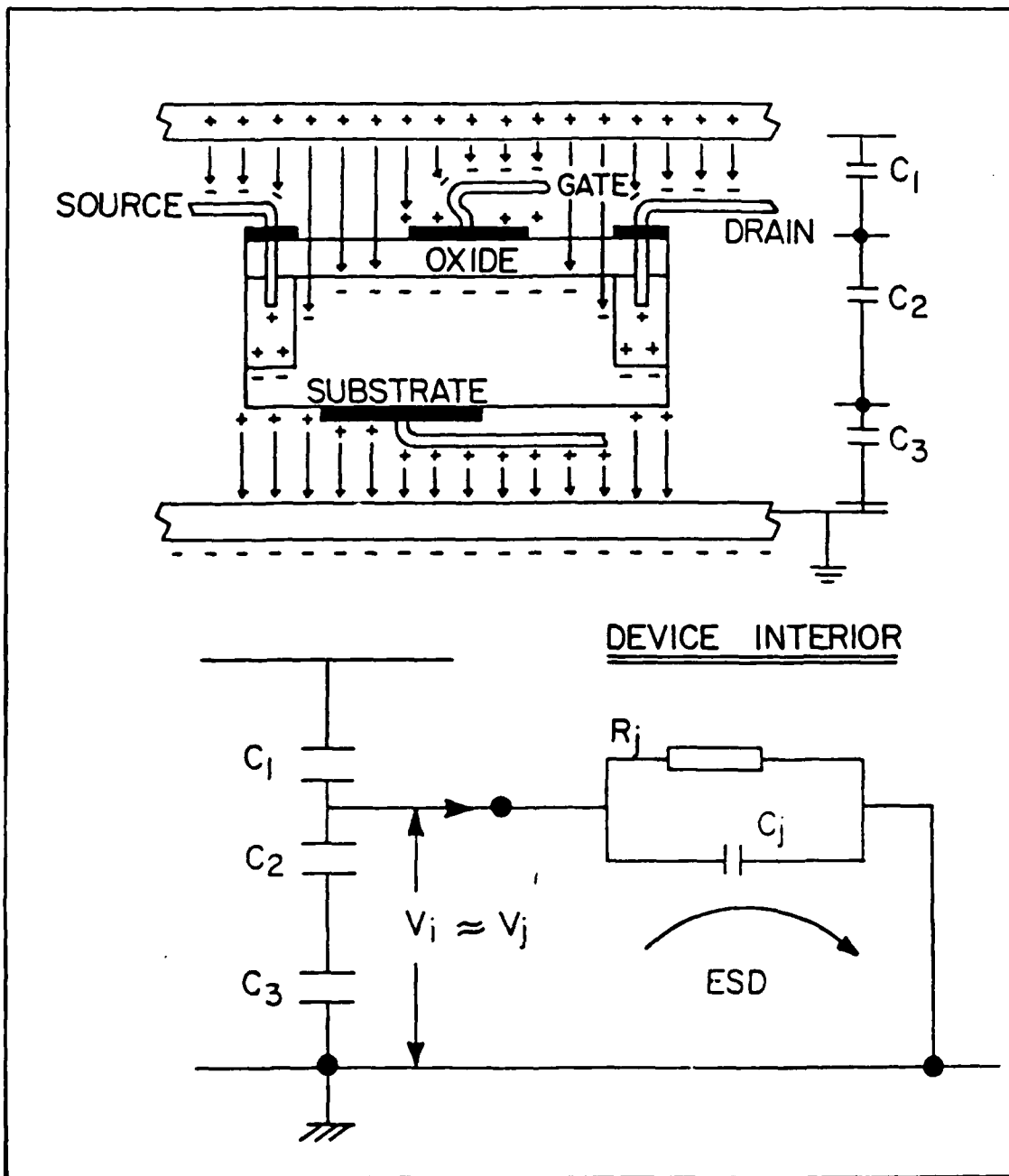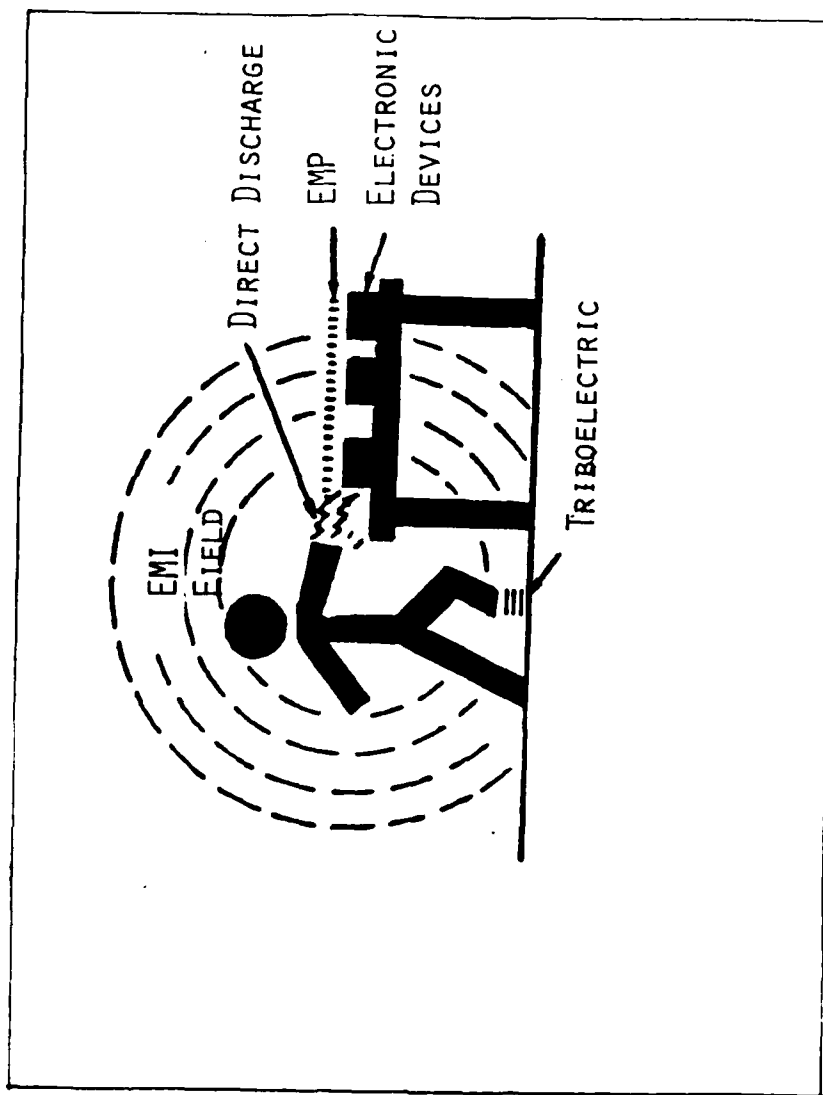FIG. 2   ESD: CHARGED DEVICE MODEL

FIG.3   ESD: FIELD - INDUCED MODEL

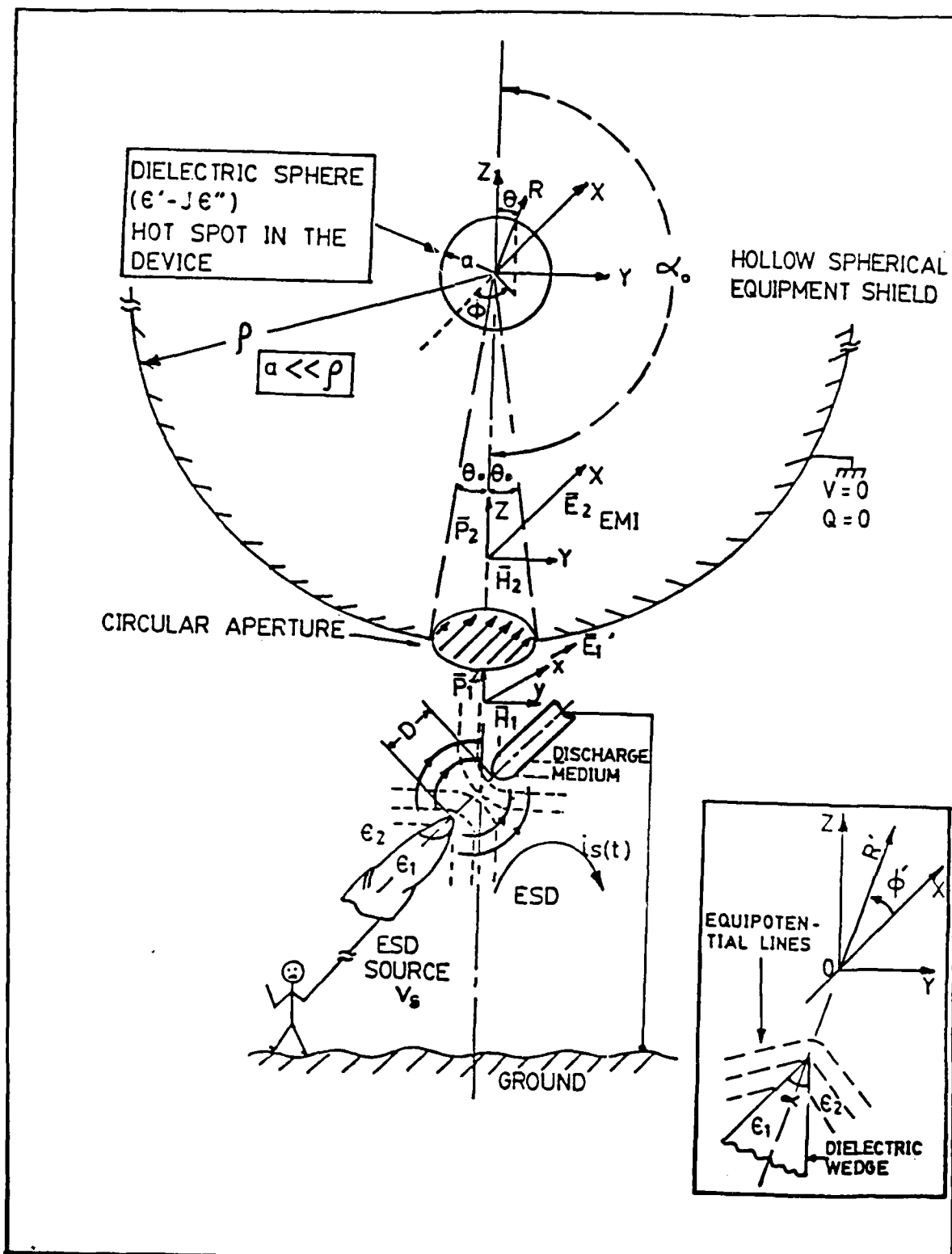Fig. 4   EMI Due To Static Effects
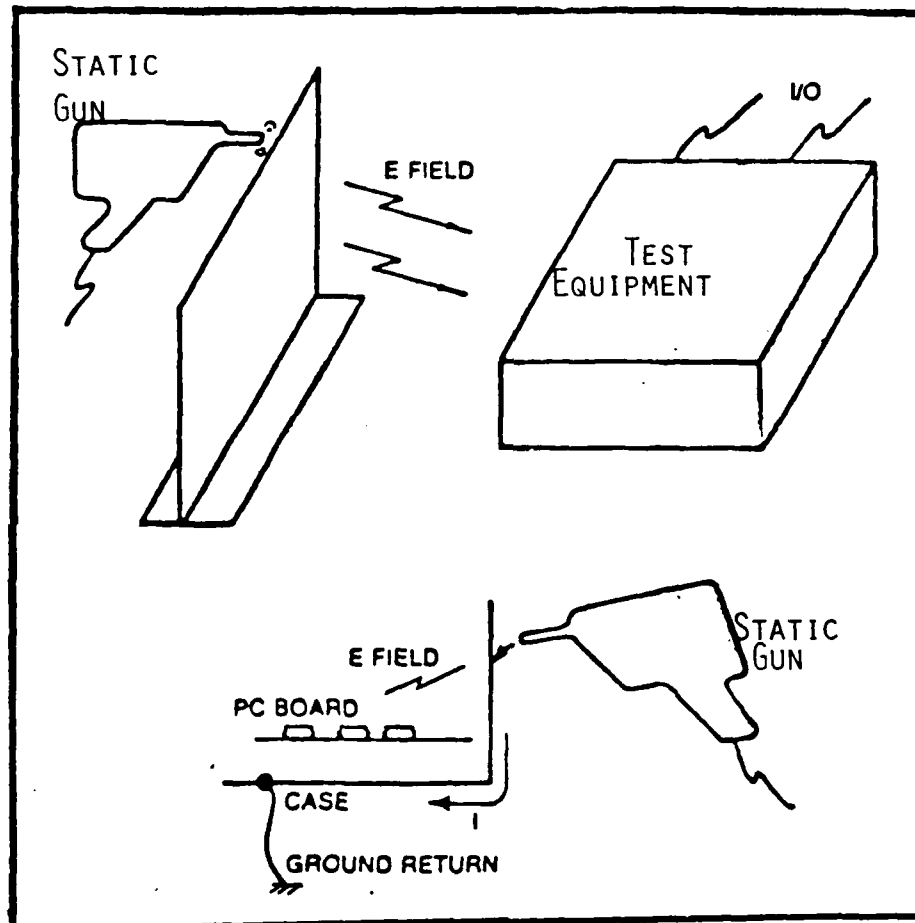
FIG. 5   ESD - BASED EMI: MODELING
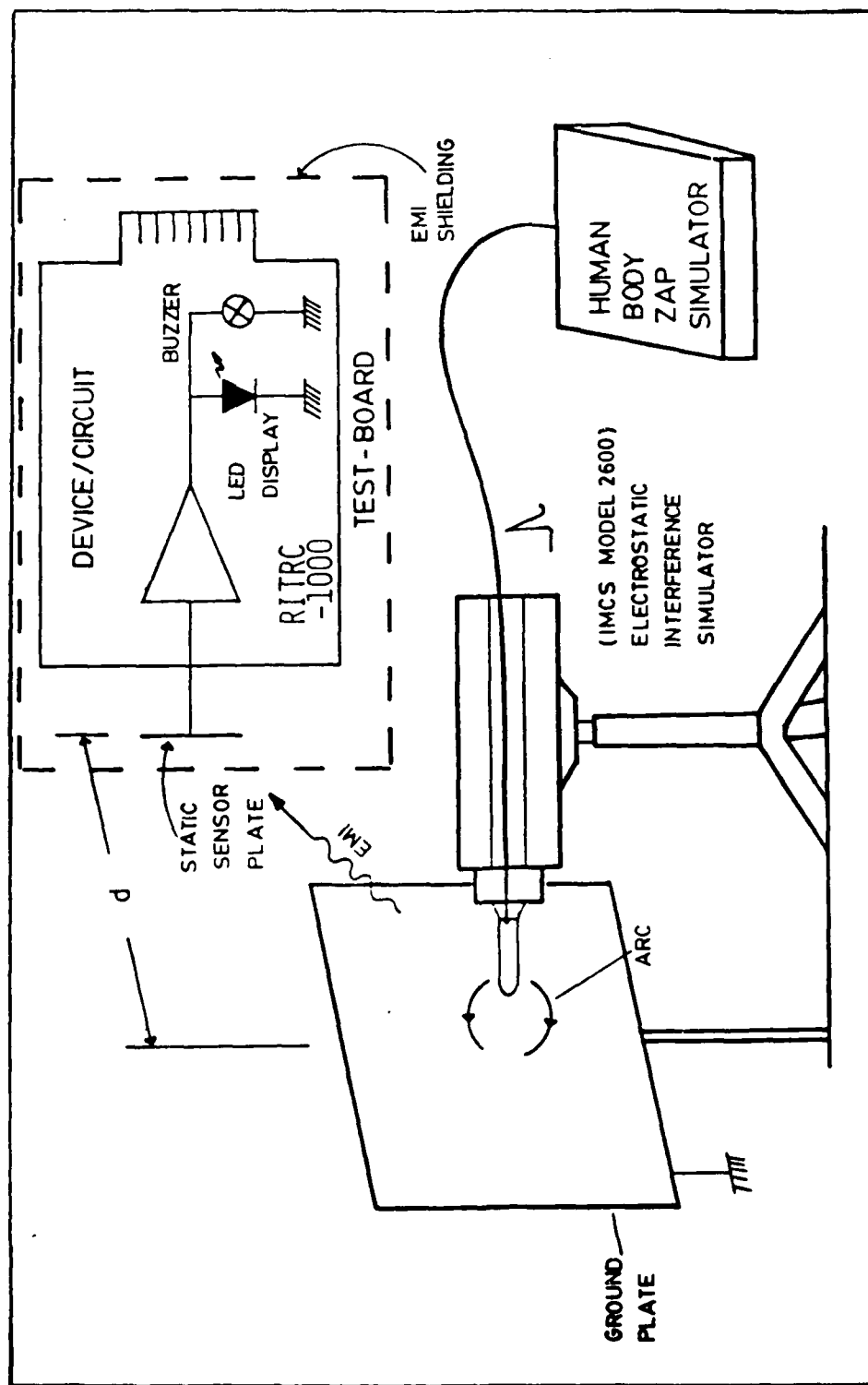
FIG. 6   PRINCIPLE OF SIMULATING ESD-BASED EMI

Fig. 7   ESD - Induced EMI Coupling To A Circuit: Experimental Set-up

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